Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Post-earthquake residual deformations and seismic performance assessment of buildings

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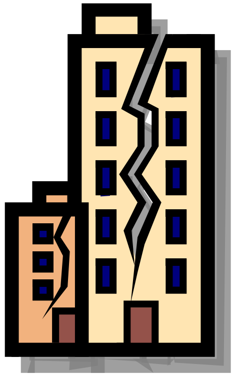
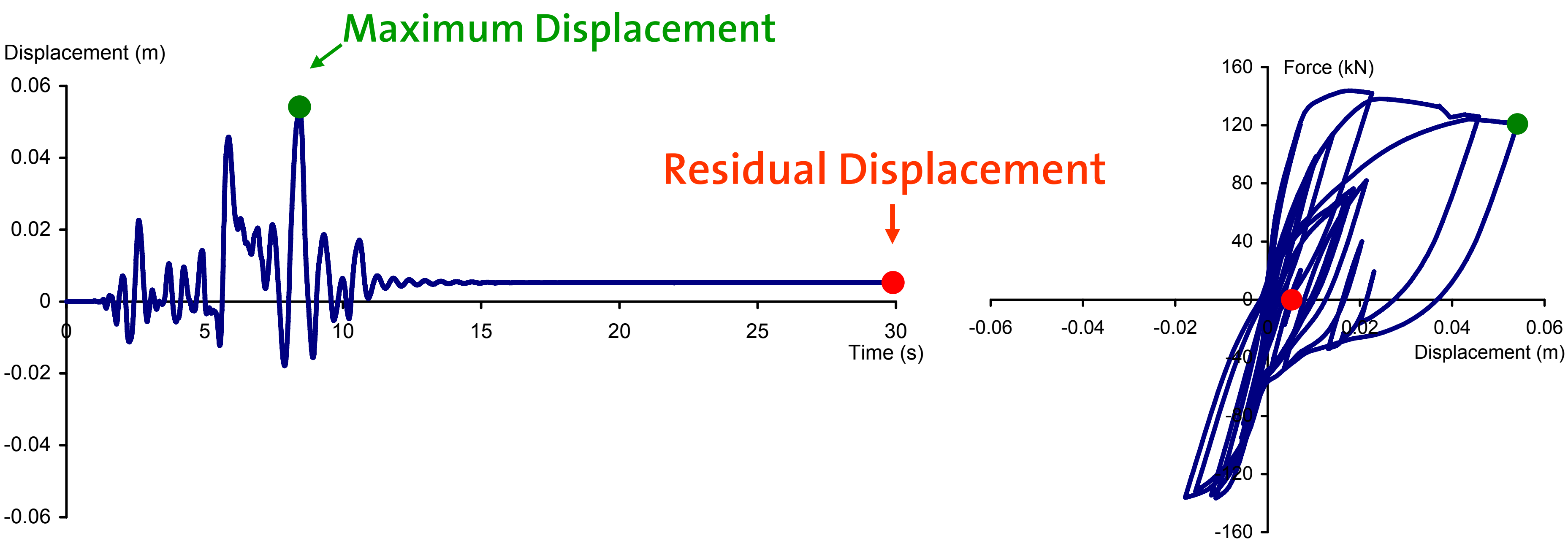
Motivation

MERCI **M**anagement of **E**arthqauke **R**isks using **C**ondition **I**ndicators



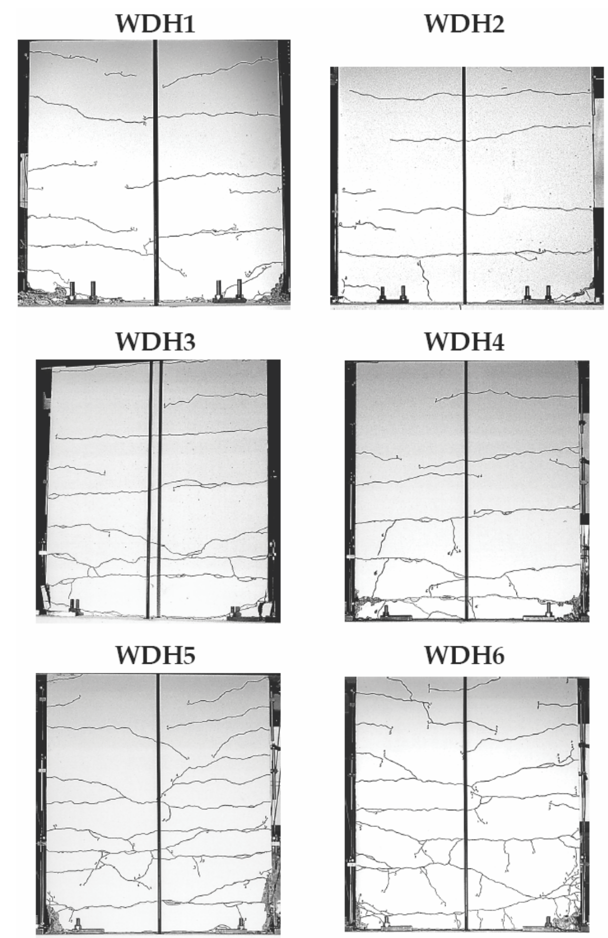
- The need to reduce the uncertainties in the assessment of seismic performance after an earthquake
- The need for a direct consideration of **post-earthquake** residual displacements in the seismic design of structures

Post-Earthquake Residual Displacements



Residual Deformations at the Component Level

Courtesy National Information Service for Earthquake Engineering, University of California, Berkeley.



(Source: Lestuzzi P., Wenk. T & Bachmann T., (1999), "Dynamische Versuche an Stahlbetontragwänden auf dem ETH-Erdbebensimulator", IBK IBK Bericht Nr. 240, April 1999)

Residual Displacements at the Structural Level

Courtesy National Information Service for Earthquake Engineering, University of California, Berkeley.

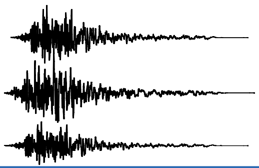
Residual Displacements due to Ground Deformations

Courtesy National Information Service for Earthquake Engineering, University of California, Berkeley.

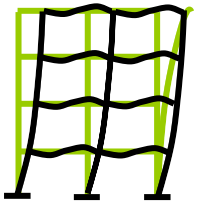
Post-Earthquake Assessment

Damaged Building

Reconnaissance Survey



Recorded Ground Motion

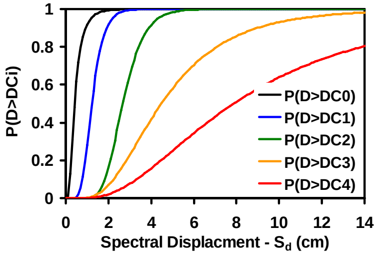


FEM Model

Measured Residual Displacements

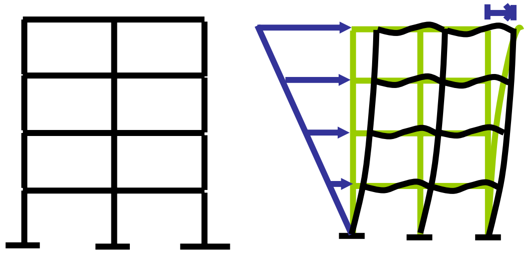
Estimates of Maximum Displacements

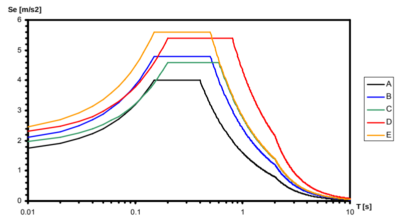
Post-Earthquake Vulnerability



A **Seismic Performance Assessment Method** for buildings based on **residual displacements** is being developed.

Performance-Based Design





FE Model

PSH Model

Seismic Performance

Estimates of Maximum Displacements

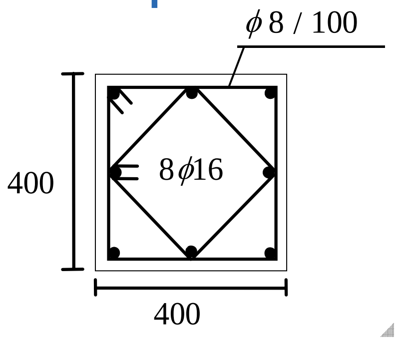
Estimates of Residual Displacements

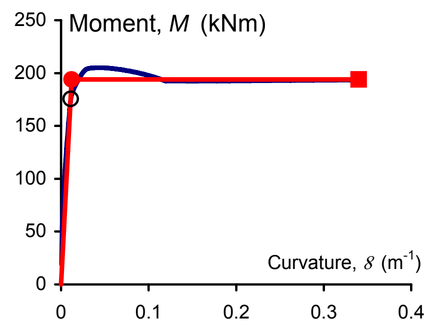
Known to be well correlated with the attained damage

Provide essential information about the the post-earthquake:
- **Reparability/Usability**
- **Vulnerability**

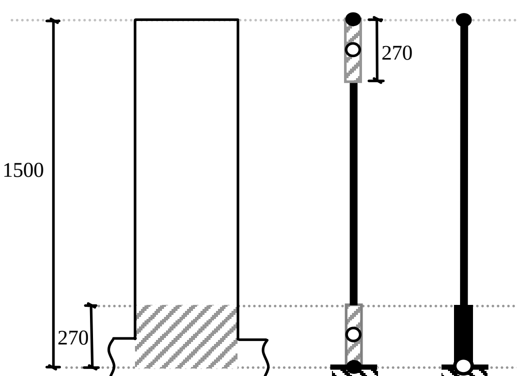
Difficulties related to simulation of response

Lumped Plasticity Models: Ruaumoko, DRAIN-2DX, OpenSees, SeismoStruct

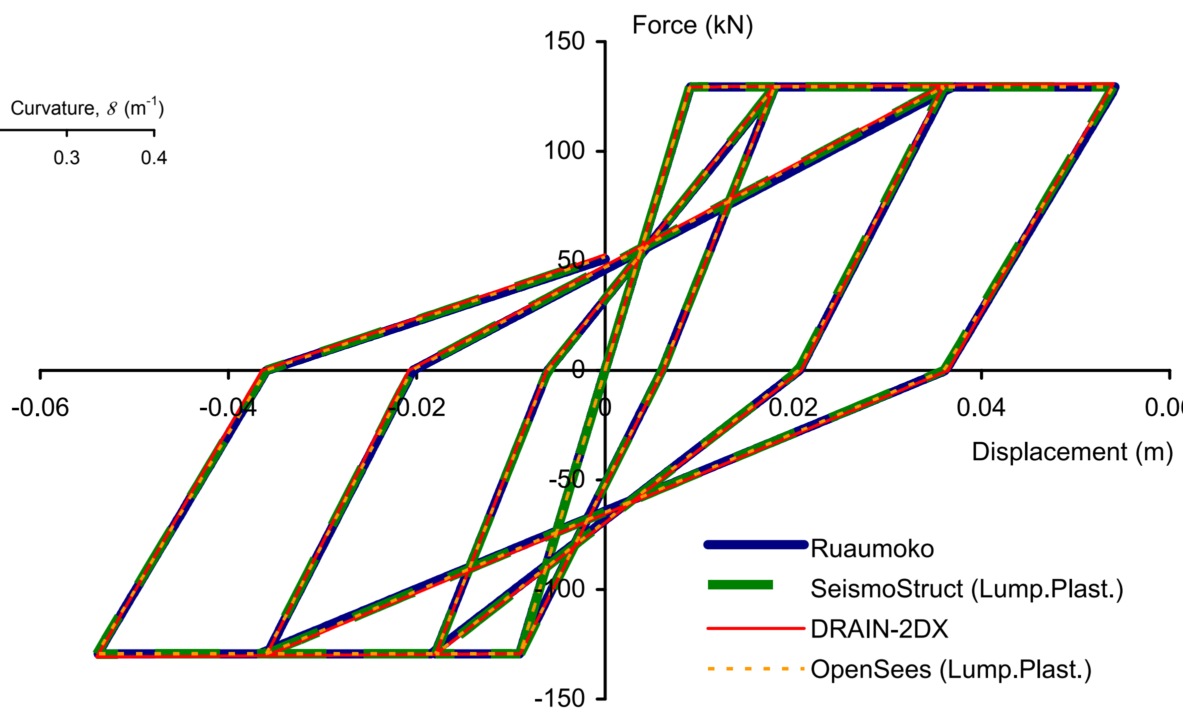




$$n = \frac{N}{A_g f_c'} = 0.2 \qquad \rho_g = 1\%$$



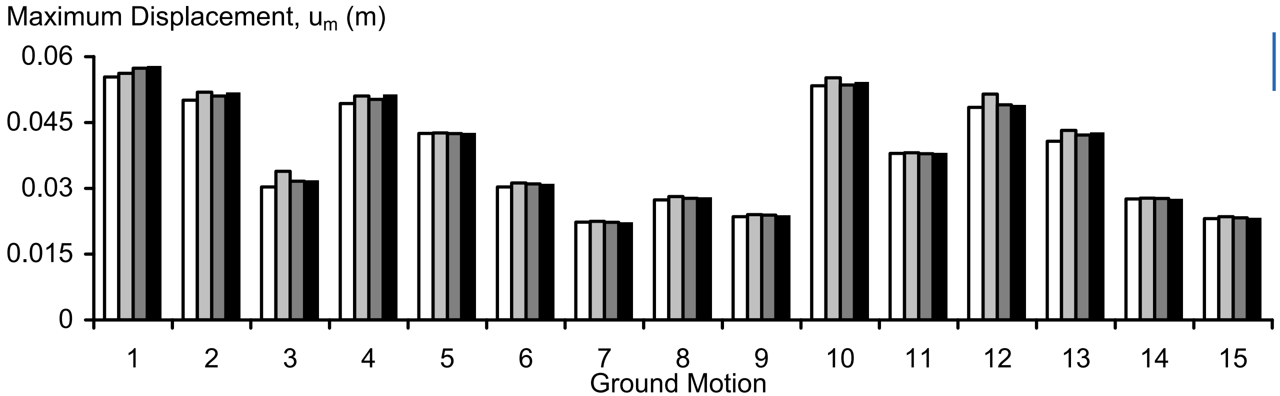
Simulated large-cycle responses ...

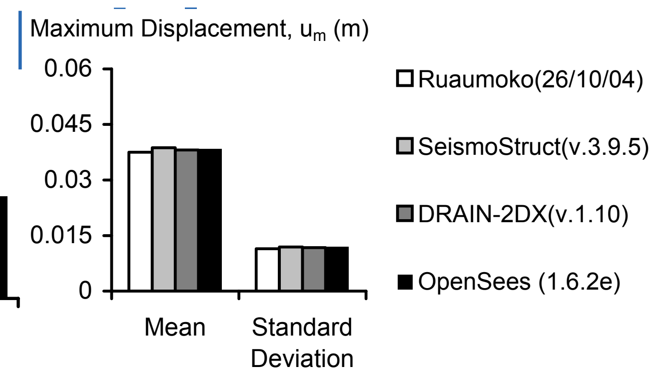


... are practically the same. ✓

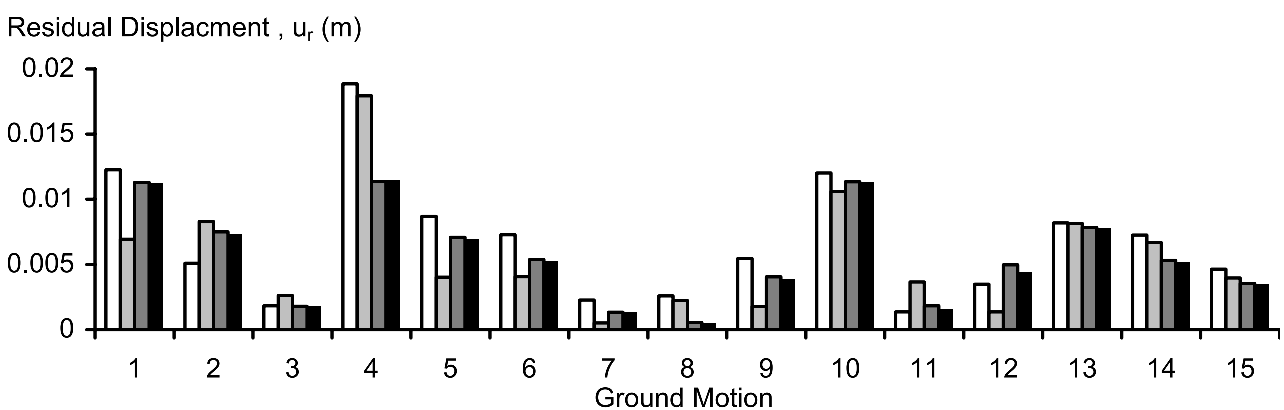
T = 0.5 [s] R_y = 4   ζ = 5%

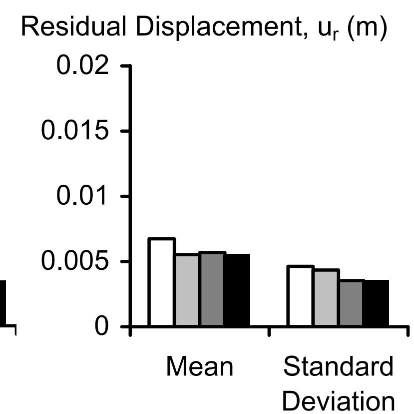
Practically, the maxima are the same ✓





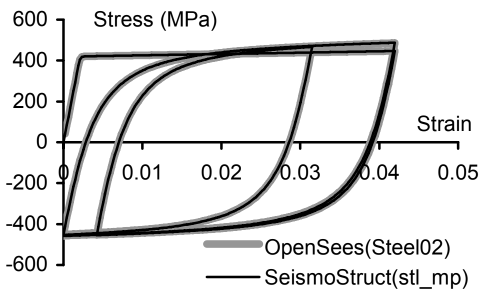
However, the residual displacements are significantly different !



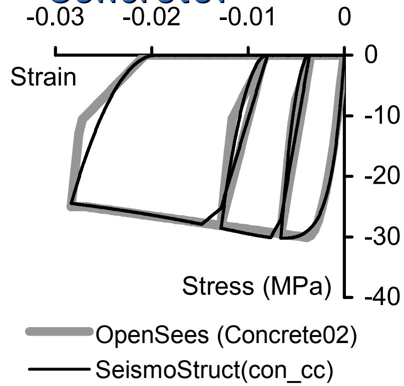


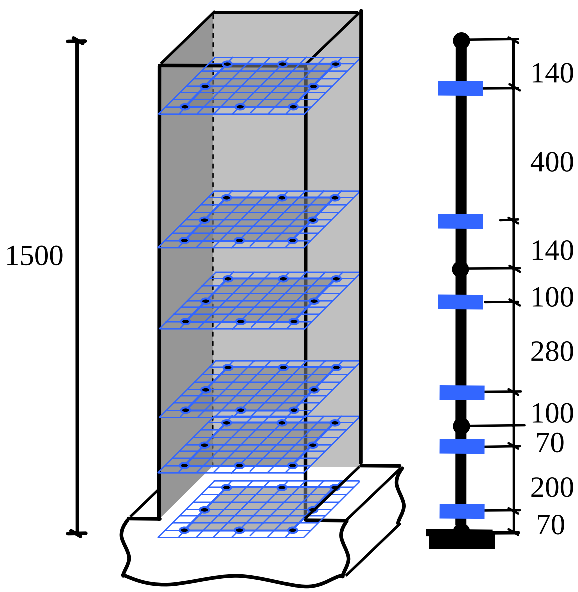
Fiber Models: OpenSees, SeismoStruct, Rechenbrett-2D

Reinforcement:

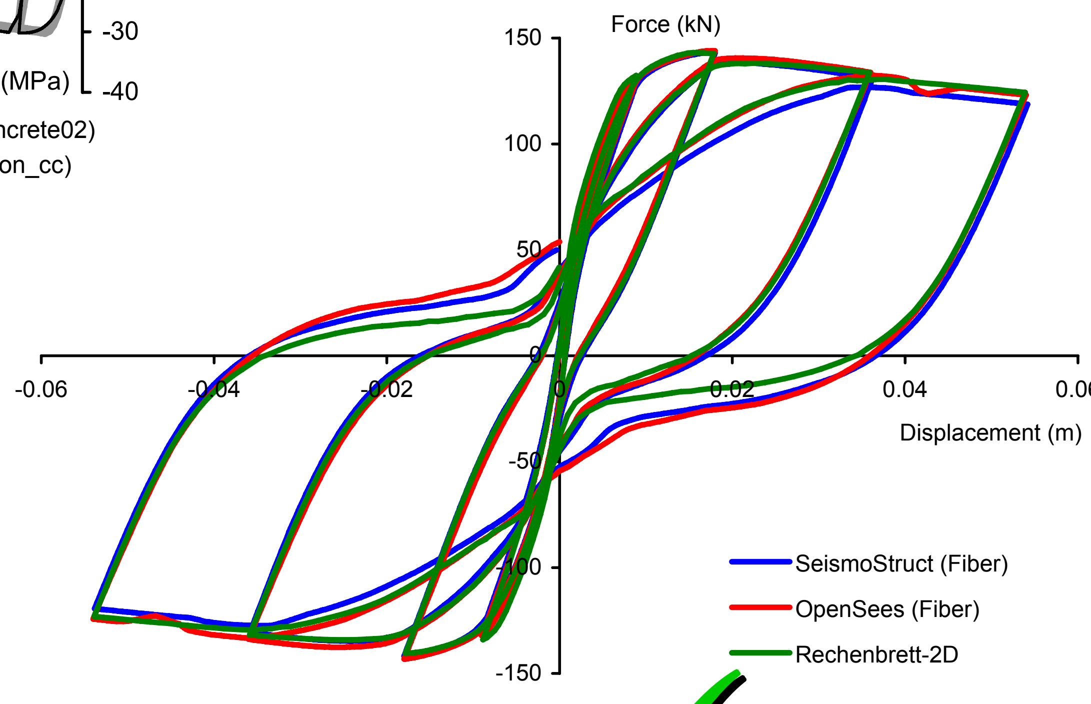


Concrete:



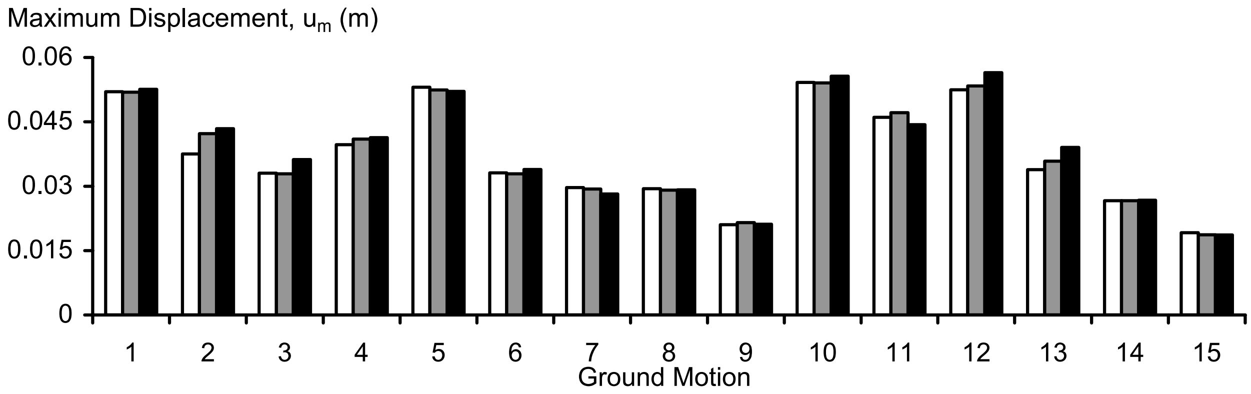


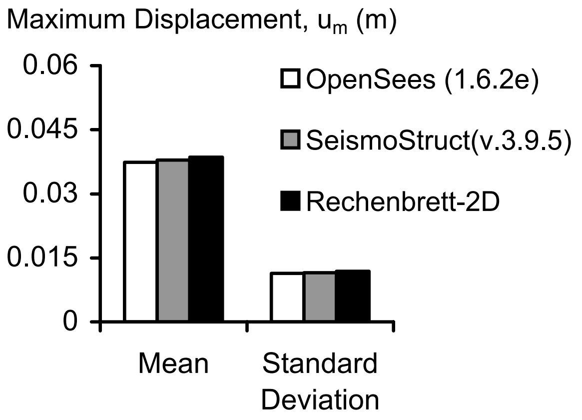
Simulated large-cycle responses ...



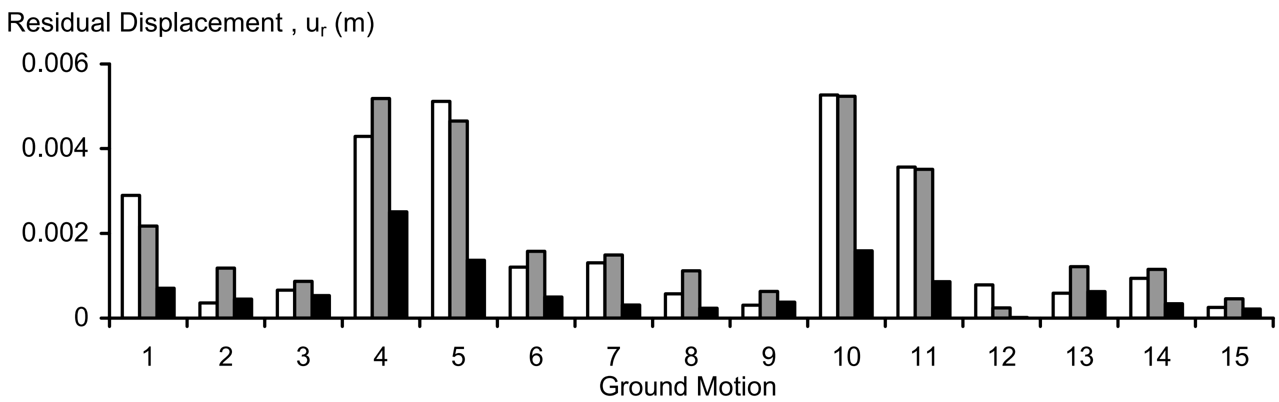
... practically the same ✔

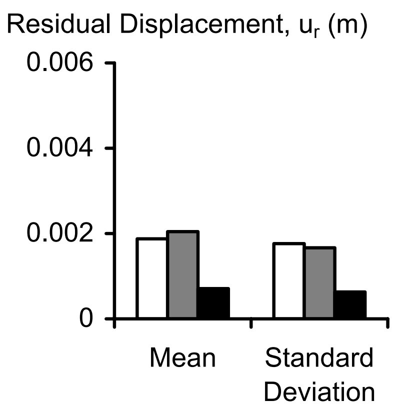
Again ... Practically, the maxima are the same ✓





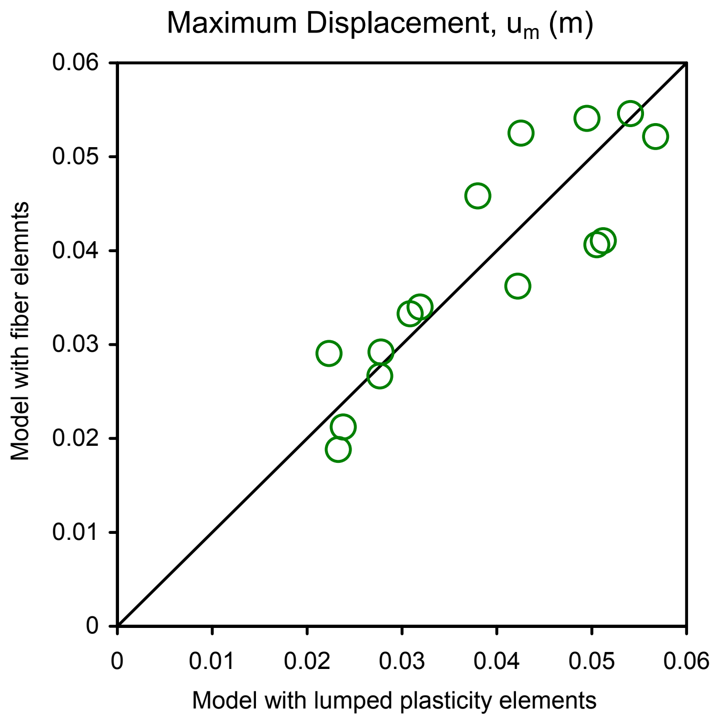
Again... the residual displacements are significantly different !



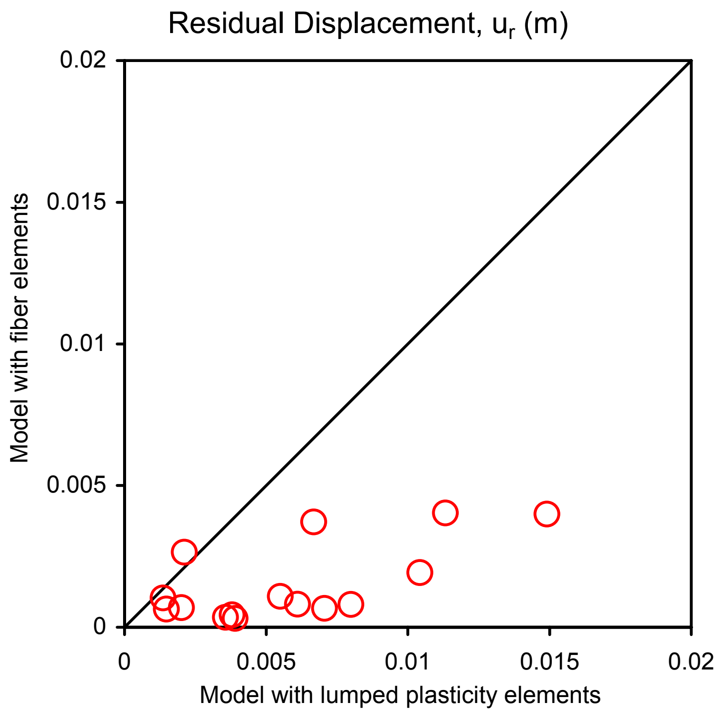


Results: Fiber vs Lumped Plasticity

Maximum Displacements



Residual Displacements

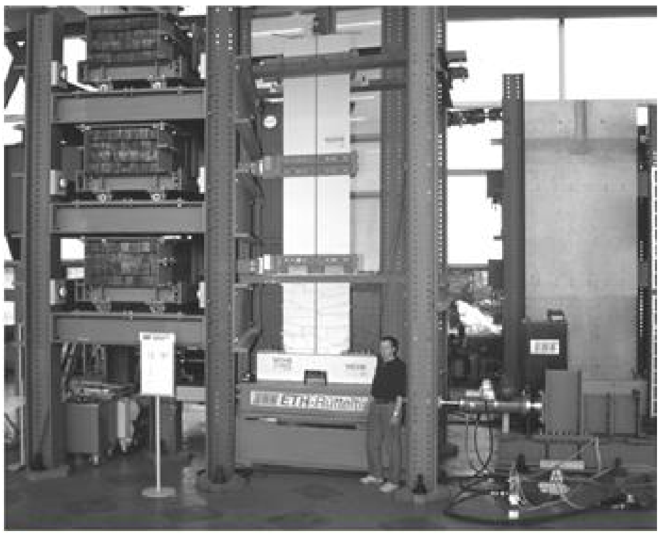


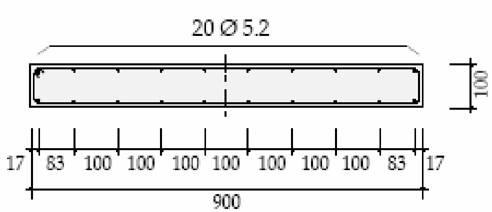
Residual displacements are significantly influenced by the <u>adopted modeling approach</u> !

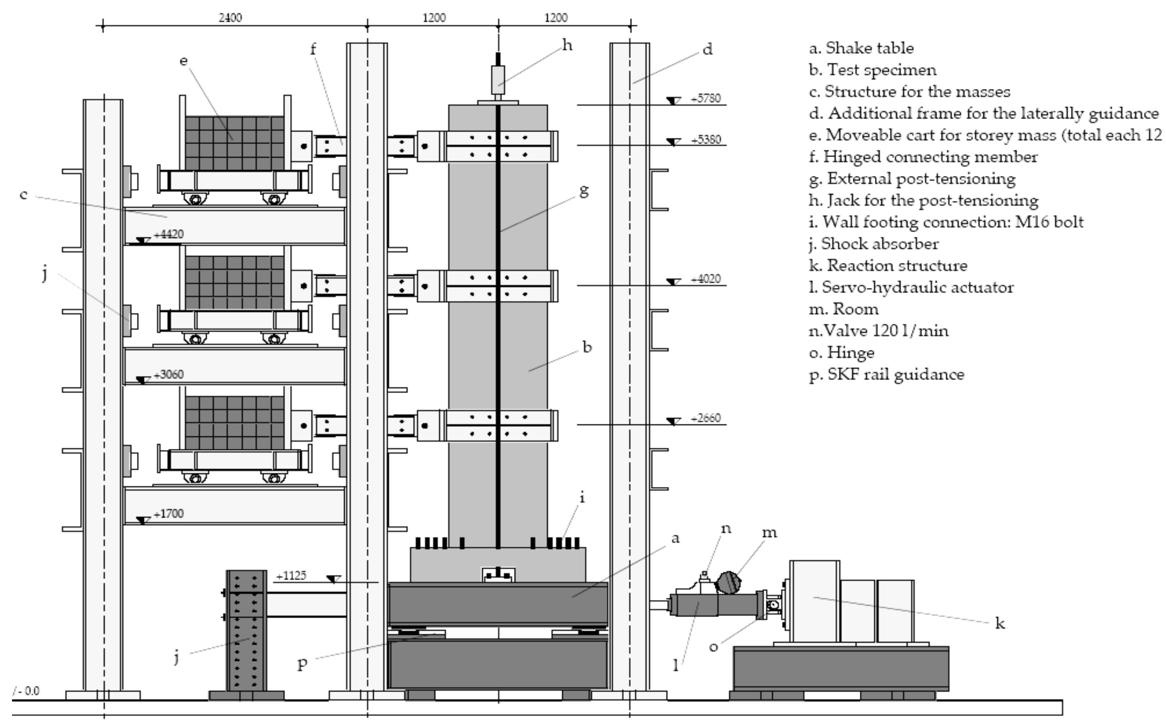
Comparison with the experimental data

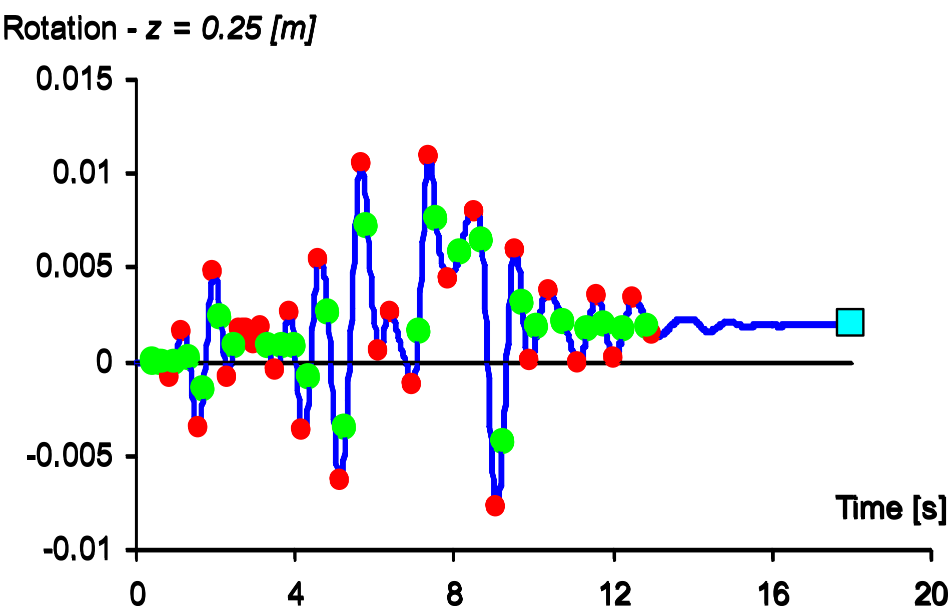
- Description of the shake table test

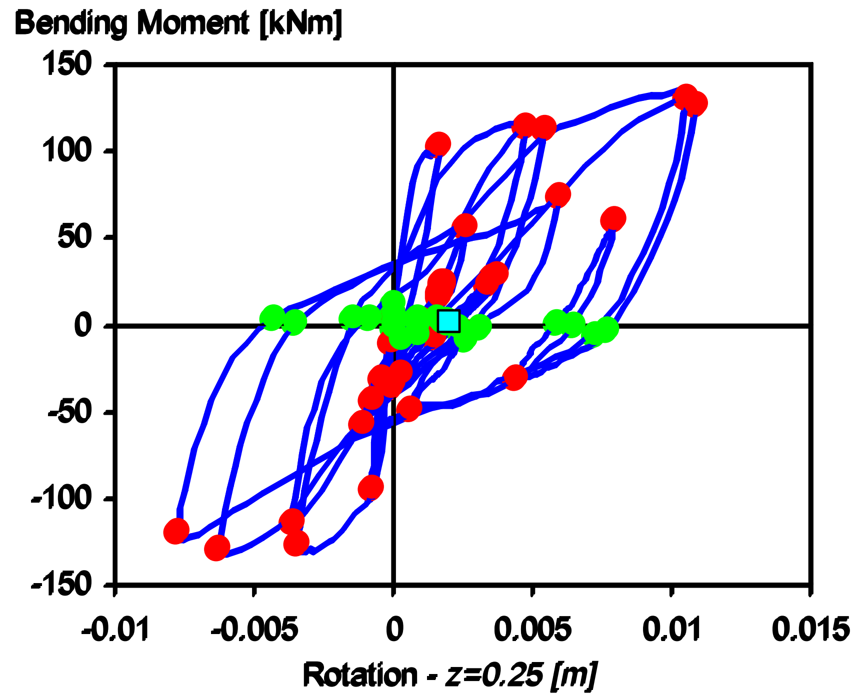
Lestuzzi, P., T.Wenk, H. Bachmann (1999), "Dynamische Versuche an Stahlbetontragwänden auf dem ETH-Erdbebensimulator", IBK Bericht Nr.240, Institut für Baustatik und Konstruktion, ETH Zürich











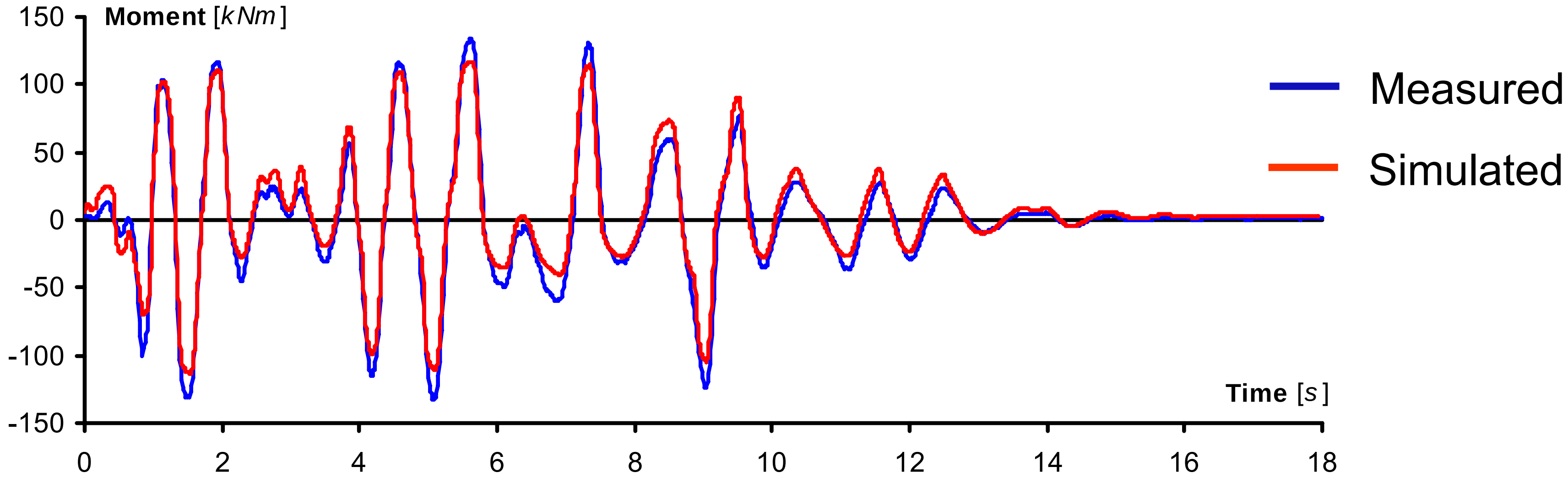
Response history

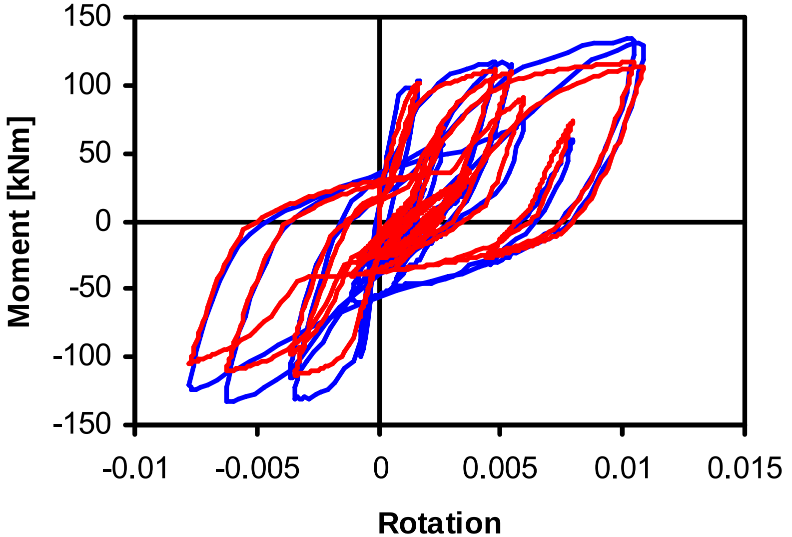
Residual deformation

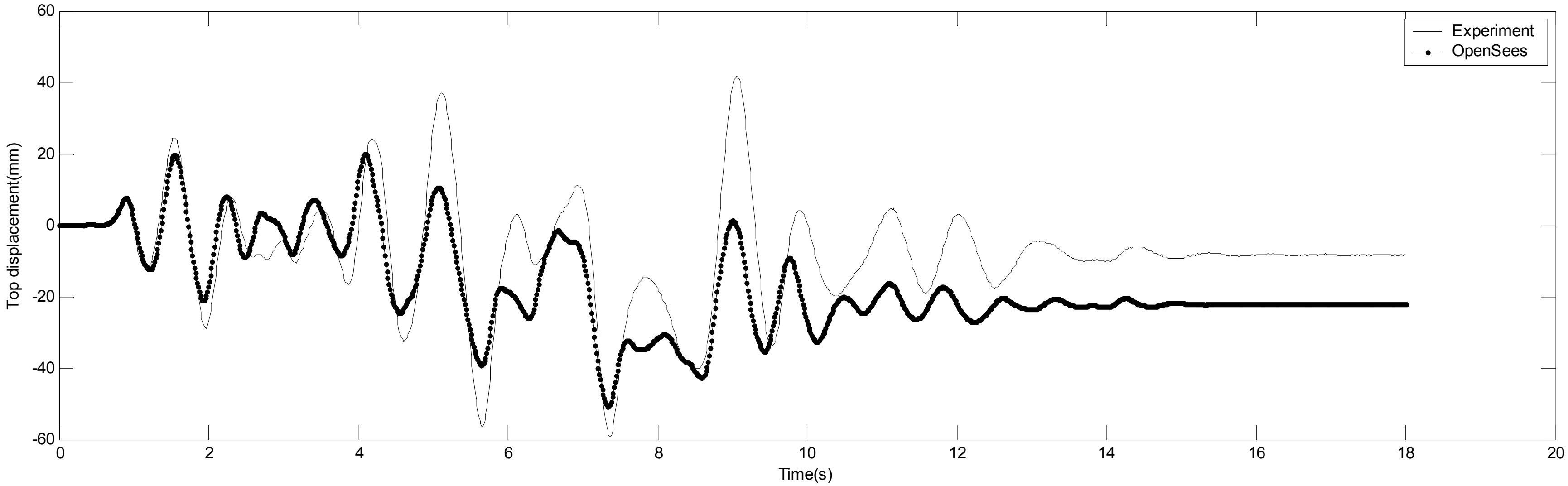
Peak deformations

Points of unloading

FE model is subjected to the measured rotation history






Experiment
OpenSees
Top displacement(mm)
Time(s)
60
40
20
0
-20
-40
-60
0
2
4
6
8
10
12
14
16
18
20

Example application

- Located in a region of high seismicity
  M_w7.4 Kocaeli, Turkey 1999 Earthquake
- Around ~7000 buildings - *mostly RC - MRF*
- Three decision alternatives:
  - strengthening the frame by structural walls
  - no action
  - preventing liquefaction by stone columns

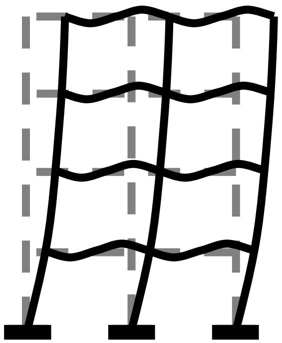
Performance of the structural stock subjected to a range of seismic events needs to be assessed.

Adapazari, Turkey

(Bayraktarli Y., U. Yazgan, A. Dazio A. and M. Faber, 2006)

Example application

- Set of representative RC frame buildings



N_{story}=1,2,3,...,7

h_{story} = 2.4 [m]

L_{bay} = 6 [m]

ε_{sy} = 2.1 [%]

A_{story}=300 [m^2]

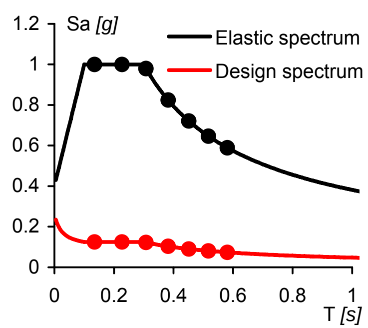
M_{story}= 0.6 [t/m^2]

Yield ground story drift, θ_y — *Priestley (1998)*

- Fundamental mode shape, ϕ_1
- Yield displacement at roof, $\Delta_{y,roof}$
- Modal participation factor, Γ_1

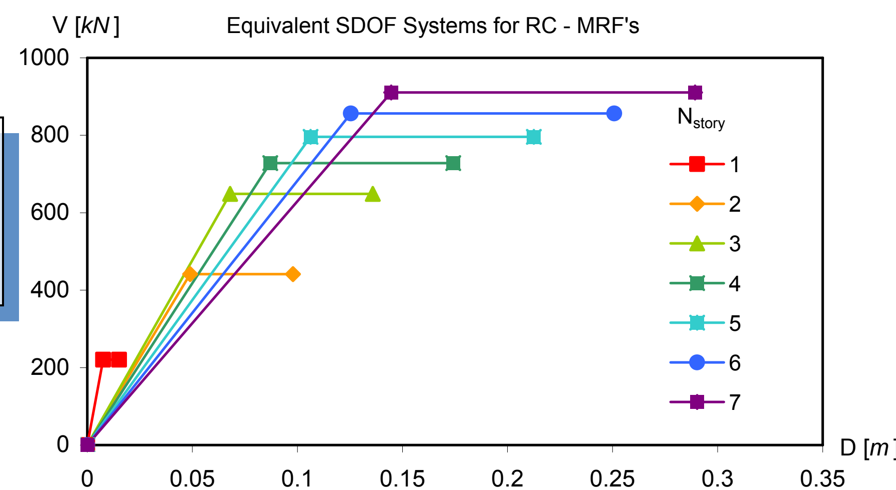
Dazio(2000)
Modal Analysis

TEC-98, ζ=5%, Z1, R=8



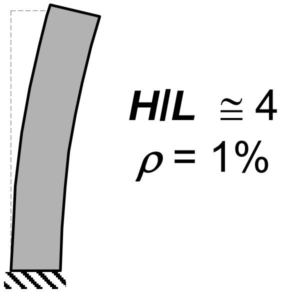
Yield displacement, Δ^*_y

Base shear capacity, V^*_y



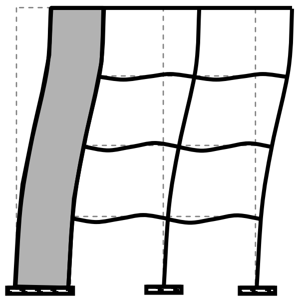
Example application

- Representative models for retrofitted buildings



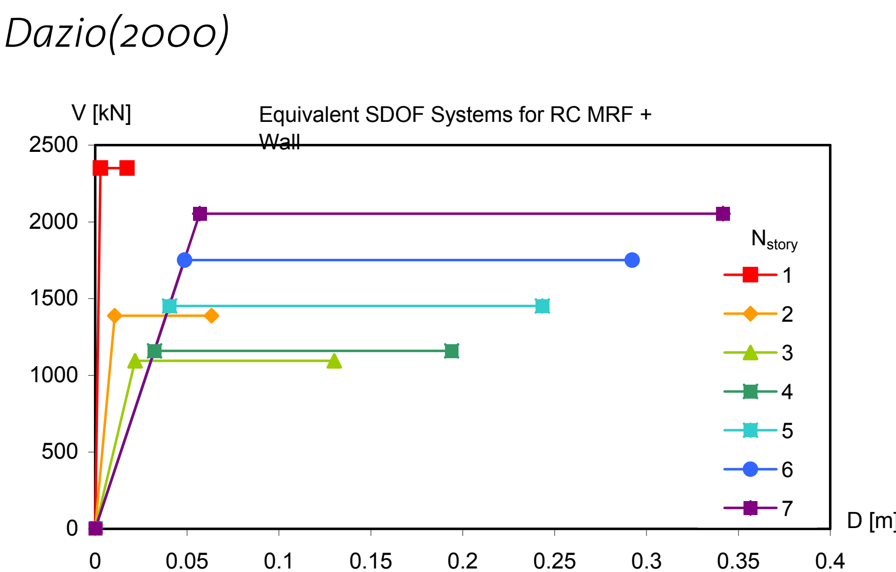
Added Structural Walls

- Yield curvature, ϕ_y
- Yield displacement at the top, $\Delta_{y,w}$
- Flexural yield strength, M_y
- Base shear at yielding V_y



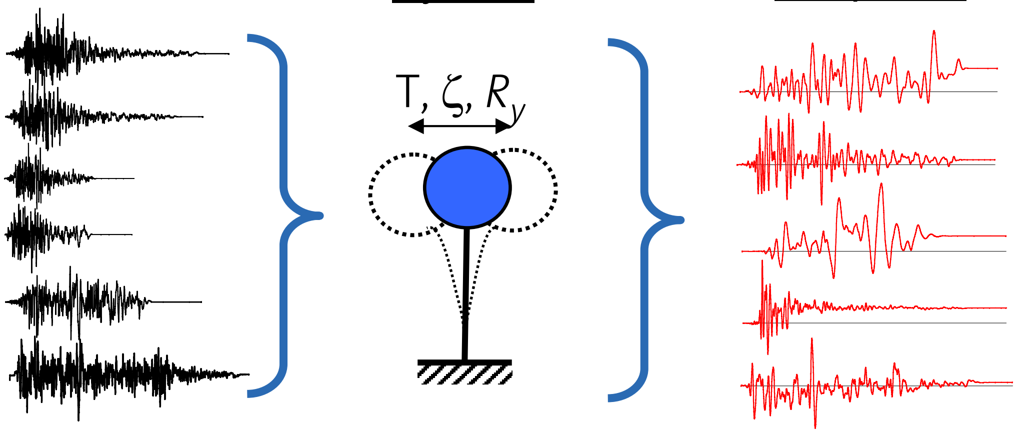
Wall +Frame System

- Yield displacement, $\Delta_{y,roof}$
- Base shear at yielding V_y



Example application

Ground Motions | Substitute SDOF System | Simulated Response

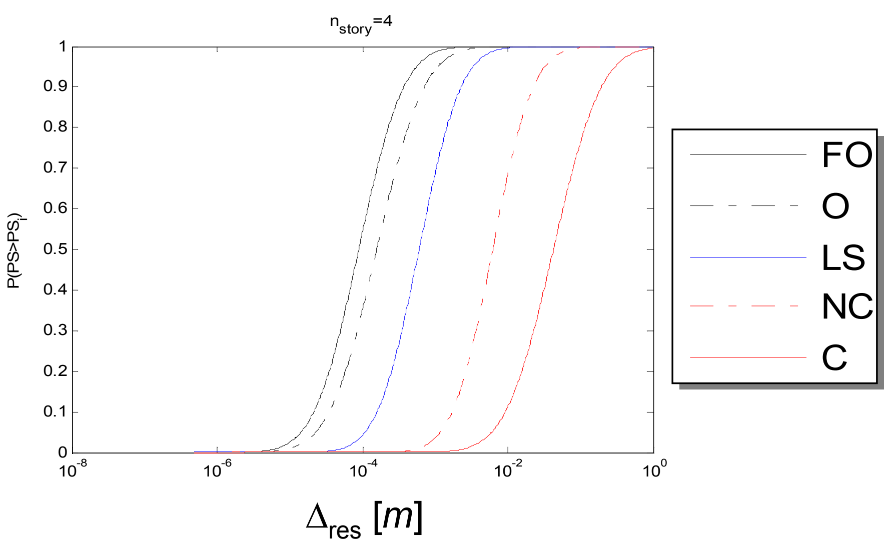


Maximum Displacement, Δ_{max}

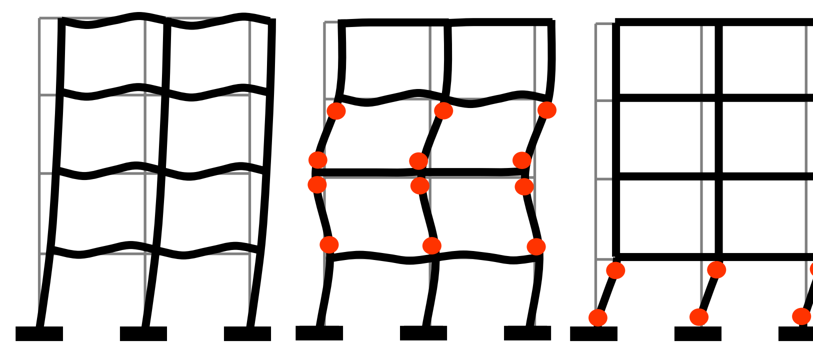
Residual Displacement, Δ_{res}

Performance State

Vision2000(1995)



Which Δ_{res} ?



Conclusions

- Residual displacements are significantly influenced by the adopted modeling approach
- It is possible to establish a performance assessment strategy taking into account residual displacements to update the uncertainties
- Further study is needed to identify:

  - Which deformations would provide an effective measure?

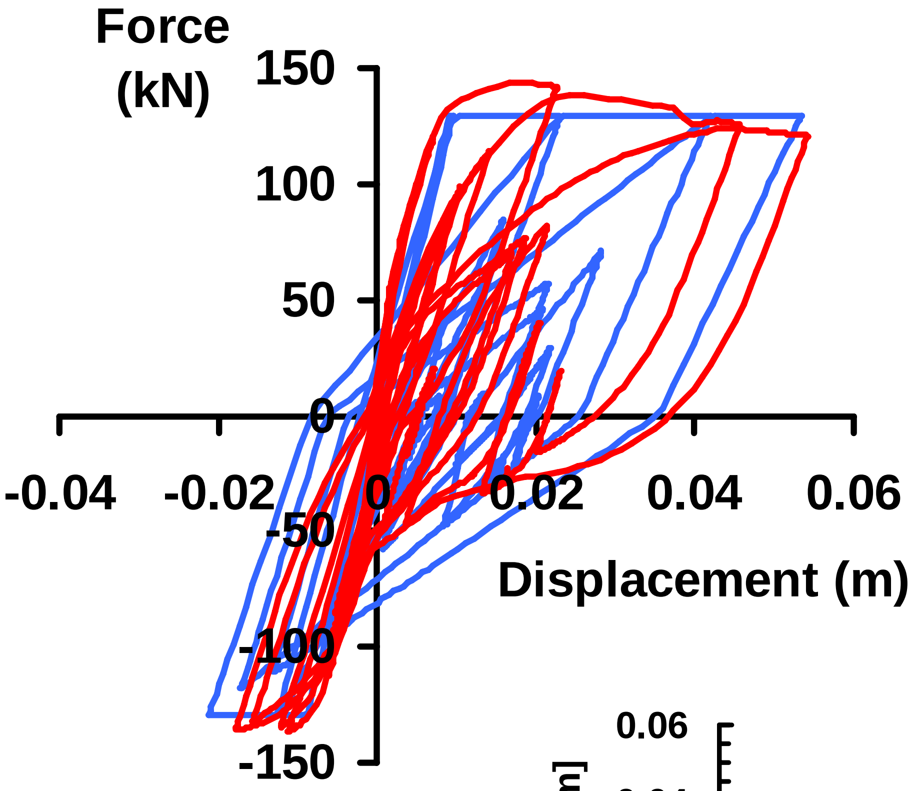
  - Which are feasible to measure?

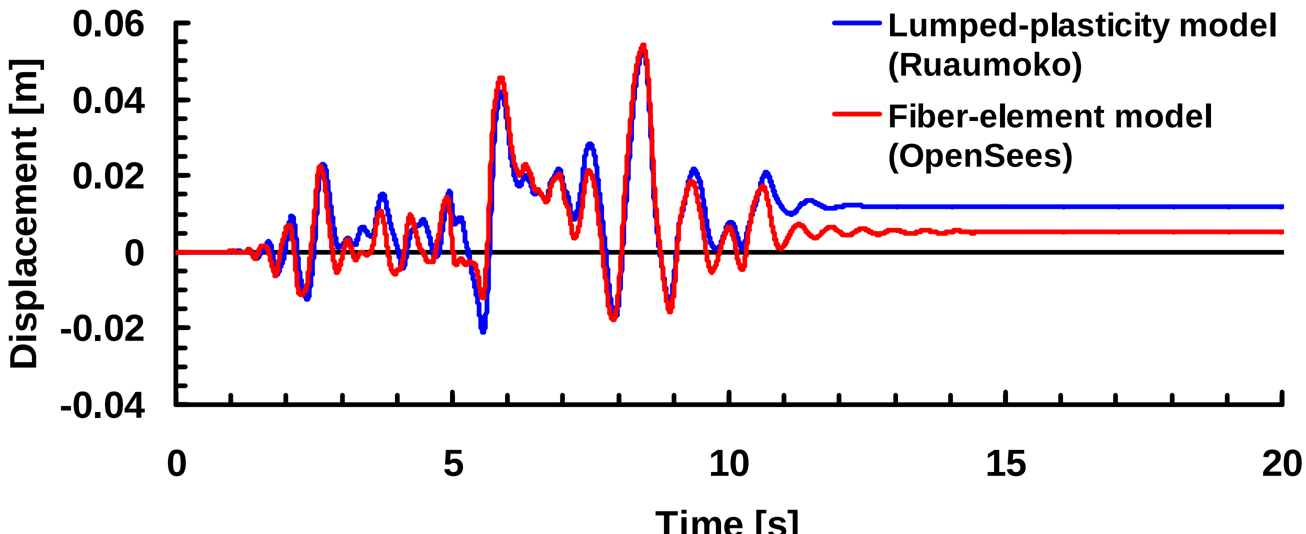
Outlook / Open Questions

- **RC frame and structural wall systems are being studied**
- **Effective intensity measures related to residual displacements are being investigated**
- **Efficient ways to relate the seismic performance to structural response parameters needs to be identified**
- **Methods to include nonlinear soil deformation in the seismic performance assessment needs to be investigated**
- **Effect of ground motion record processing schemes on the simulated residual displacements needs to be studied**

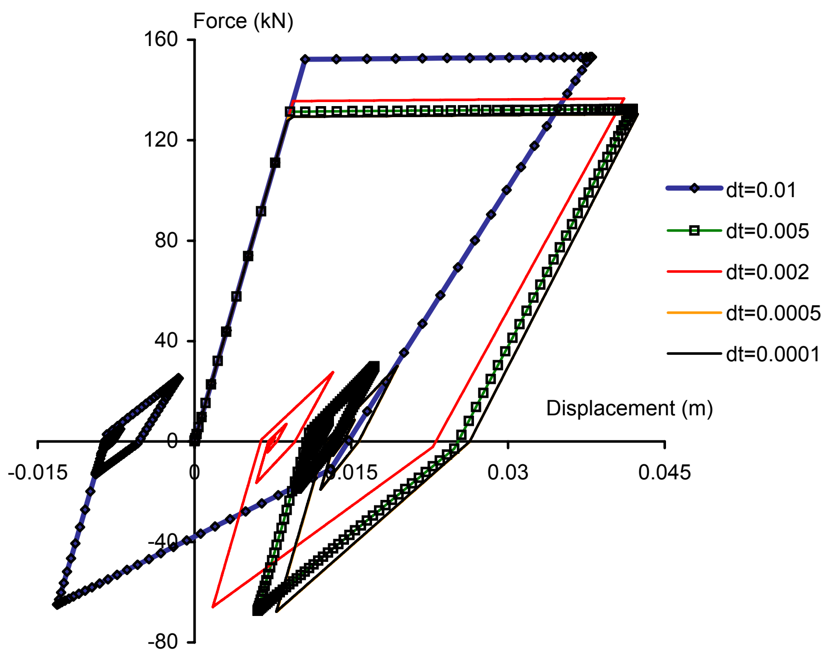
Thank you

Any Questions?

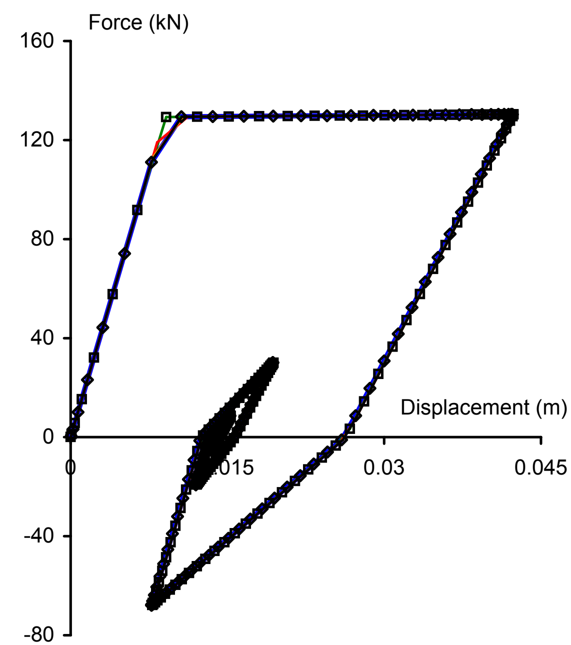

Force
(kN)
150
100
50
0
-50
-100
-150
-0.04
-0.02
0
0.02
0.04
0.06
Displacement (m)


Displacement [m]
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
Time [s]
Lumped-plasticity model
(Ruaumoko)
Fiber-element model
(OpenSees)

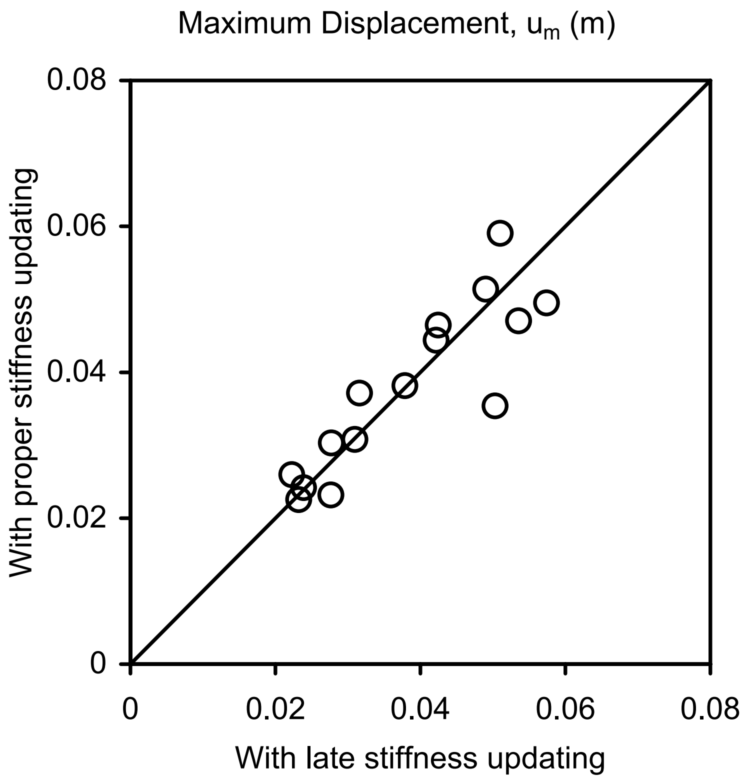
Imprtance of “time integration step size” and proper updating of stiffness

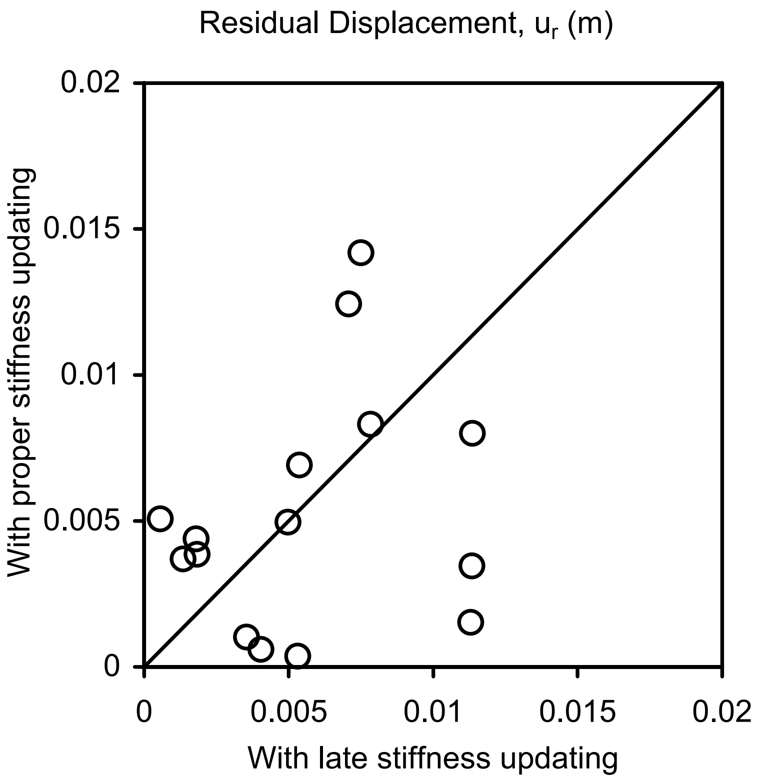


Stiffness is updated at the end of each step



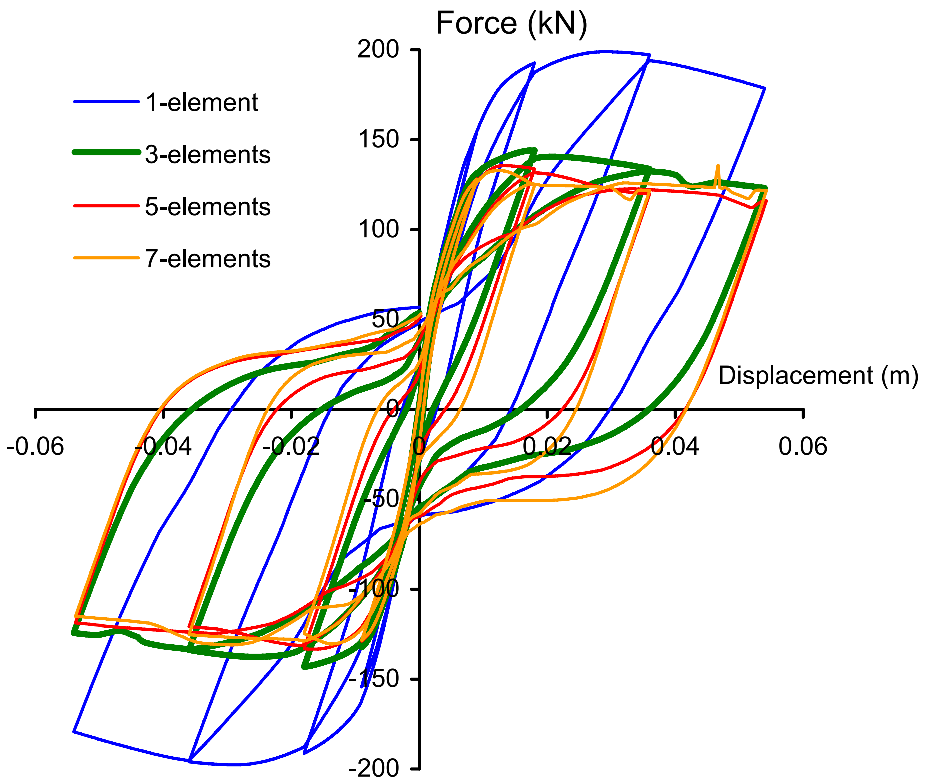
Stiffness is updated within each step



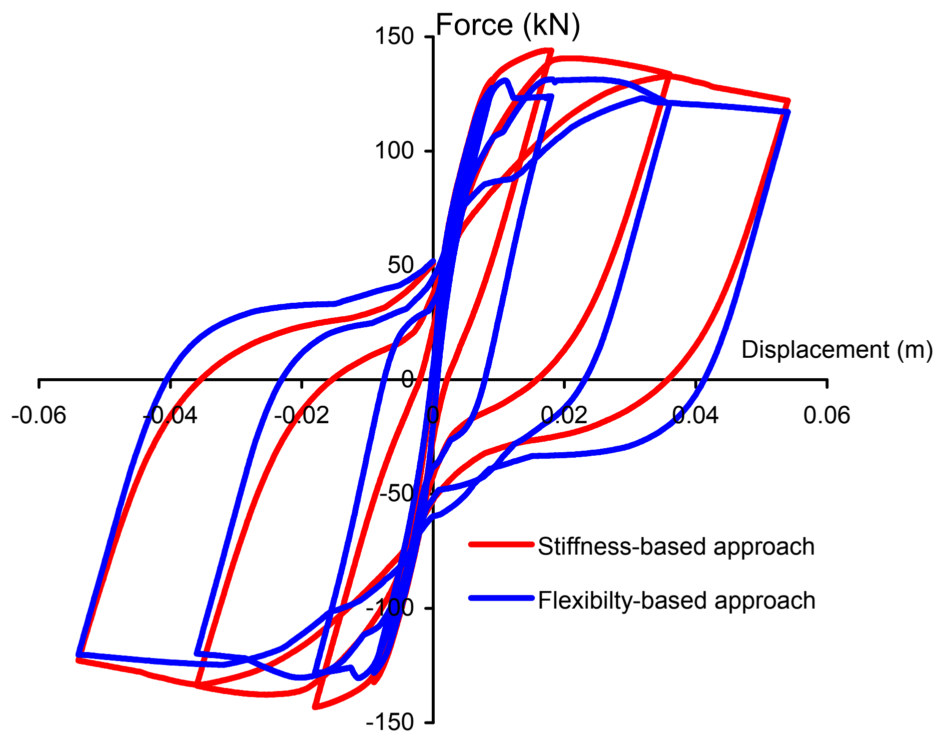


Properly updating stiffness is crucial for estimating the residual displacements !

Effect of mesh density

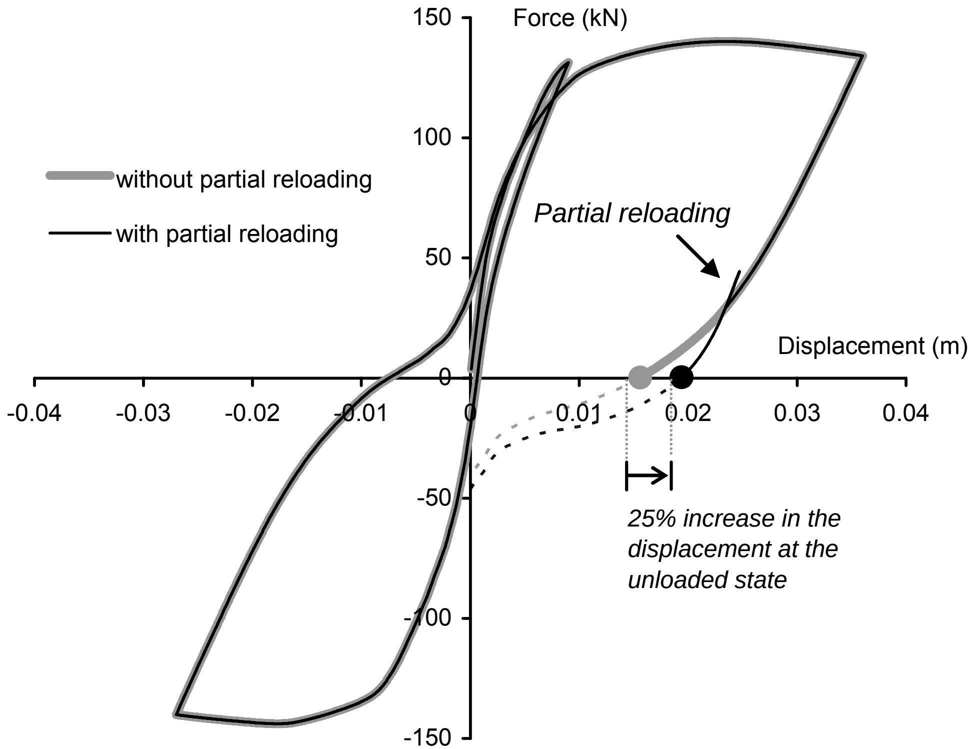


Effect of element formulation

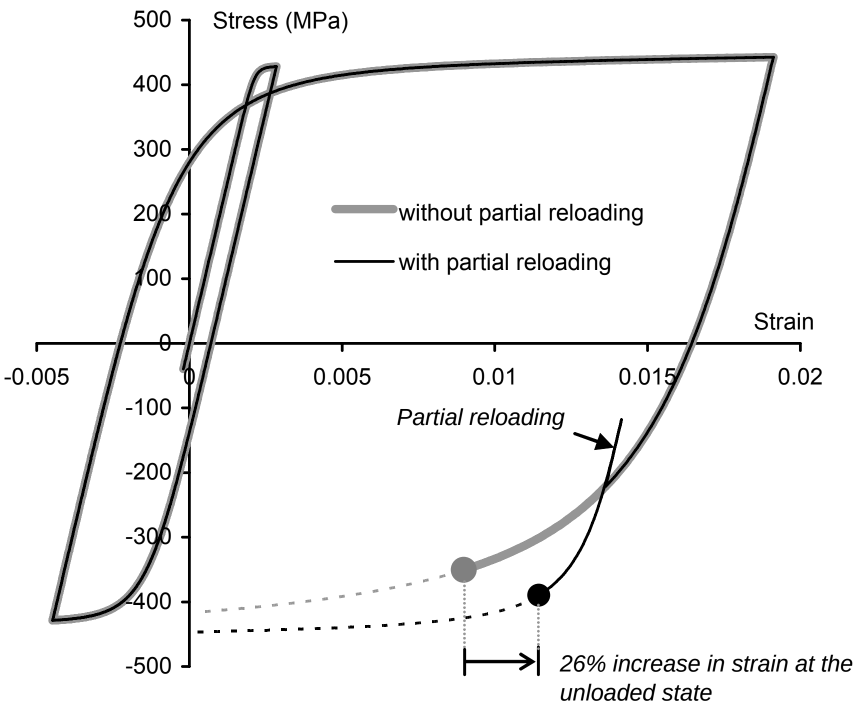


Limited memory problem of the steel hysteresis:

Force - Displacement



Steel Stress-Strain



Properly simulating the response of steel is critical for estimating the residual displacements !

- **Residual displacements are significantly influenced by the adopted modeling approach**
- **Differences in the small-cycle response leads to notably different residual displacement estimates**
- **“Time integration step size” can have a strong effect on the computed residual displacements**
- **Meshing of the system may have a significant influence on the computed residual displacements**
- **“Memory limitation” problem related to steel hysteresis response results inappropriate unloading paths**

Limit State Drifts

Calculation of limit state displacements

Maximum Displacements

H_{story}= 2.4 *[m] - Height of a story*

		$\theta_{1st\ Story}$					$\Delta_{1st\ Story}$				
	H_N	FO	O	LS	NC	C	FO	O	LS	NC	C
n_{story}	[m]	<				>	<[m]	[m]	[m]	[m]	[m]>
1	2.4	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
2	4.8	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
3	7.2	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
4	9.6	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
5	12	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
6	14.4	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06
7	16.8	0.002	0.005	0.015	0.025	0.025	0.0048	0.012	0.036	0.06	0.06

Vision 2000 (1995)

MRF

			$\Delta^*=\Delta_{1stStory} / (\Gamma\phi_{1,1})$				
	$\phi_{1,1}$	Γ	FO	O	LS	NC	C
n_{story}			<[m]	[m]	[m]	[m]	[m]>
1	1.000	1.000	4.80E-03	1.20E-02	3.60E-02	6.00E-02	6.00E-02
2	0.618	1.171	6.63E-03	1.66E-02	4.97E-02	8.29E-02	8.29E-02
3	0.445	1.220	8.84E-03	2.21E-02	6.63E-02	1.11E-01	1.11E-01
4	0.347	1.241	1.11E-02	2.78E-02	8.35E-02	1.39E-01	1.39E-01
5	0.285	1.252	1.35E-02	3.37E-02	1.01E-01	1.68E-01	1.68E-01
6	0.241	1.258	1.58E-02	3.96E-02	1.19E-01	1.98E-01	1.98E-01
7	0.209	1.262	1.82E-02	4.55E-02	1.36E-01	2.27E-01	2.27E-01

Dazio(2000) Dazio(2000)

MRF + SW

			$\Delta^*=\Delta_{1stStory} / (\Gamma\phi_{1,1})$				
	$\phi_{1,1}$	Γ	FO	O	LS	NC	C
n_{story}			<[m]	[m]	[m]	[m]	[m]>
1	1.000	1.000	4.80E-03	1.20E-02	3.60E-02	6.00E-02	6.00E-02
2	0.321	1.197	1.25E-02	3.13E-02	9.38E-02	1.56E-01	1.56E-01
3	0.156	1.291	2.38E-02	5.94E-02	1.78E-01	2.97E-01	2.97E-01
4	0.093	1.347	3.85E-02	9.63E-02	2.89E-01	4.82E-01	4.82E-01
5	0.061	1.384	5.68E-02	1.42E-01	4.26E-01	7.10E-01	7.10E-01
6	0.043	1.410	7.84E-02	1.96E-01	5.88E-01	9.80E-01	9.80E-01
7	0.032	1.430	1.04E-01	2.59E-01	7.77E-01	1.30E+00	1.30E+00

Dazio(2000) Dazio(2000)

Residual Displacements

		$\theta_{1st\ Story}$					$\Delta_{1st\ Story}$				
	H_N	FO	O	LS	NC	C	FO	O	LS	NC	C
n_{story}	[m]	<				>	<[m]	[m]	[m]	[m]	[m]>
1	2.4	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
2	4.8	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
3	7.2	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
4	9.6	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
5	12	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
6	14.4	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06
7	16.8	0.001	0.002	0.005	0.025	0.025	0.0024	0.0048	0.012	0.06	0.06

Vision 2000 (1995)

MRF

			$\Delta^*=\Delta_{1stStory} / (\Gamma\phi_{1,1})$				
	$\phi_{1,1}$	Γ	FO	O	LS	NC	C
n_{story}			<[m]	[m]	[m]	[m]	[m]>
1	1.000	1.000	2.40E-03	4.80E-03	1.20E-02	6.00E-02	6.00E-02
2	0.618	1.171	3.32E-03	6.63E-03	1.66E-02	8.29E-02	8.29E-02
3	0.445	1.220	4.42E-03	8.84E-03	2.21E-02	1.11E-01	1.11E-01
4	0.347	1.241	5.57E-03	1.11E-02	2.78E-02	1.39E-01	1.39E-01
5	0.285	1.252	6.74E-03	1.35E-02	3.37E-02	1.68E-01	1.68E-01
6	0.241	1.258	7.91E-03	1.58E-02	3.96E-02	1.98E-01	1.98E-01
7	0.209	1.262	9.09E-03	1.82E-02	4.55E-02	2.27E-01	2.27E-01

MRF + SW

	$\phi_{1,1}$	Γ	FO	O	LS	NC	C
n_{story}			<[m]	[m]	[m]	[m]	[m]>
1	1.000	1.000	2.40E-03	4.80E-03	1.20E-02	6.00E-02	6.00E-02
2	0.321	1.197	6.26E-03	1.25E-02	3.13E-02	1.56E-01	1.56E-01
3	0.156	1.291	1.19E-02	2.38E-02	5.94E-02	2.97E-01	2.97E-01
4	0.093	1.347	1.93E-02	3.85E-02	9.63E-02	4.82E-01	4.82E-01
5	0.061	1.384	2.84E-02	5.68E-02	1.42E-01	7.10E-01	7.10E-01
6	0.043	1.410	3.92E-02	7.84E-02	1.96E-01	9.80E-01	9.80E-01
7	0.032	1.430	5.18E-02	1.04E-01	2.59E-01	1.30E+00	1.30E+00

Dazio(2000) Dazio(2000)